AC 2008-672: INTERDISCIPLINARY DESIGN, A CASE STUDY ON STUDENTS' EXPERIENCE IN THE P3 COMPETITION

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Interdisciplinary Design
A Case Study on Students' Experience in the P3 Competition

Abstract

Teaching green design in academia is challenging. Due to its very nature, green design is interdisciplinary. On the other hand, in a typical case in academia, there tends to be a separation between disciplines. This paper reports on the experience of a group of undergraduate students; who, while participating in the national sustainable design competition (P3 competition), were asked to perform an interdisciplinary design task. The subject of this interdisciplinary design competition was to design an adaptive sustainable manufactured home, which is energy-efficient, adaptive, portable, affordable, aesthetically-pleasing, and can be manufactured locally. The paper thoroughly explains the design challenge, the performance-based objectives, the quantitative design-assisting tools used by the students, four examples of the students' work, quantitative findings, and conclusions of the design competition.

1. Introduction: P3 Competition

The P3 Competition is a national student sustainable design competition sponsored by the EPA (U.S. Environmental Protection Agency). It is a competition to the benefit of People, Prosperity, and the Planet (P3). One of the competition's primary goals is to disseminate the concept of sustainable design in higher education, which subsequently makes it an appropriate vehicle for introducing interdisciplinary design to university students.

The authors of this paper agree with the understanding of sustainability as a "design approach"[1], which is certainly a holistic (i.e., interdisciplinary) approach that takes into account all related externalities in order to solve a specific design problem. The authors were awarded $10,000 from the EPA, which they used to integrate the P3 competition as an educational tool in an elective course they co-taught on sustainable design. The design project, explained below, was the required final assignment in the course, in which students were expected to apply the knowledge and skills they acquired during the semester on the topic of "Sustainable Design in Architecture".

2. Design Competition Entry

The subject, chosen by the faculty, for this competition entry was "The Chameleon House, an Adaptive Sustainable Manufactured Home". In this design challenge, participating student teams were asked to generate concept designs for a manufactured home that uses minimal amount of purchased energy to provide heating and cooling for its occupants. The objective was to design a portable house that can adapt to the possible range of climatic conditions within the geographic borders of the State of Oklahoma.

3. Interdisciplinary Design & the Integrated Design Method

Working on the P3 competition, eight student teams enjoyed the challenge and understood the crucial role of inter-disciplinary design in creating a sustainable building. The design challenge required students to perform inter-disciplinary tasks, in which each team had to simultaneously

develop an architectural design for a residential unit and estimate its environmental performance. Students coupled their architectural and engineering skills. Students experienced first hand how to guide the design process toward producing a sustainable product (building). The cornerstone to the success of this experience was the use of quantitative design-assisting tools to provide instant evaluation of the environmental performance of the dwelling unit during the design process. This parallel instant quantitative analysis helped students make the right design decisions at the right time, i.e., early enough during the design process. It is worth mentioning that this design development process that is guided by a simultaneous analytical feedback is often referred to as the "Integrated Design Method"[2] [Figure 1].

Design-assisting tools used during this integrated design process helped students to perform the required tasks, which were: pre-design climatic analysis, solar control studies, heating load calculations, cooling load calculations, and PV sizing calculations. These quantitative design-assisting tools proved to be very stimulating to the students. In a typical architectural design process, quantitative evaluations take place only at the end of the design process, which usually results in losing any opportunity to develop energy-efficient or sustainable buildings; a fact that made the Chameleon House project an unusual beneficial experience to the students.

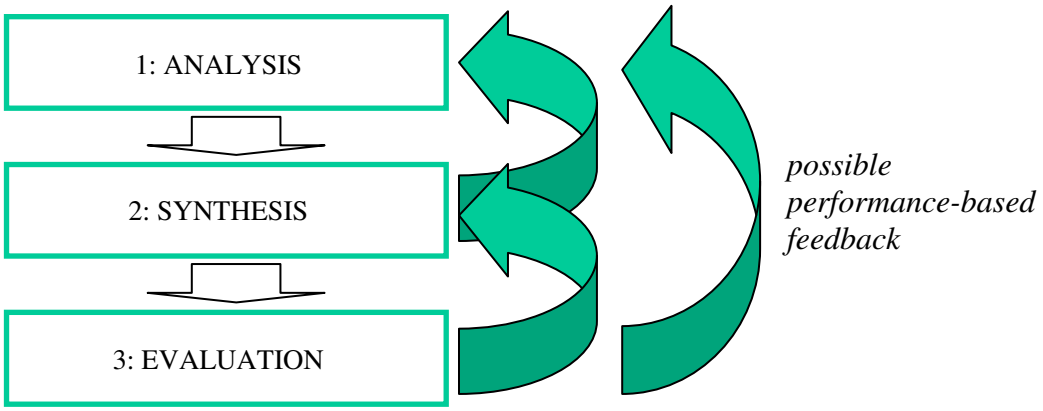

Figure 1: The Integrated Design Method

4. The Design Process

The project started similar to any typical architectural design project, however because of the nature of the Integrated Design Method, the design process started with a clear focus on the building's context (climate) and environmental performance. A detailed description of the design process as explained to and experienced by the students is below.

4.1 Project Description

This project challenged students as responsible architects, engineers, and citizens of the world to design an Adaptive Sustainable Manufactured Home. At minimum, this home is expected to be energy efficient, adaptive, portable, and affordable. Students were expected to come up with innovative yet realistic solutions. For every design solution, students were asked to rigorously address the following specific issues:

Energy Efficiency:

1- The home should utilize a passive solar heating system that can provide 100% required heating to meet the worst case scenario, i.e., January 21st or December 21st.
2- The home should utilize a passive cooling system that can help minimize the need for mechanical cooling.
3- The home should enjoy the thermal flywheel effect of thermal mass, by means of using refillable water bags to create thermal mass within the building's envelope.
   [Note] Super insulation of the envelope outside of the thermal mass is one of the most successful energy conserving measures for houses in Oklahoma climate.
   [Note] In order to control passive solar heating systems, indirect heat gain and isolated heat gain systems are much more desirable than direct heat gain systems.

Adaptability:

4- The home should be adaptable to the range of climatic conditions that is possible within the borders of the State of Oklahoma.
5- The home should be adaptable to different possible site orientations.
   [Note] Adaptability to a wide range of climatic conditions may be achieved through the utilization of adjustable shading devices. Adaptability to different site orientations may be achieved through the utilization of inter-changeable building parts and flexible design.

Mobility:

6- The home should be portable, i.e., lightweight at the time of shipping. This can be achieved by the use of refillable water tanks/bags as thermal mass.
7- The home can be shipped in smaller pieces that do not exceed the maximum allowable dimensions of: 14'x 60'x 13' (WxLxH)[3].
   [Note] In the US, 19.7% of existing manufactured homes moved at least once from the site of their first installation to another site[4].

Affordability:

8- The design solution should be realistic, i.e., suggests reasonable solutions and technologies, and can be manufactured in Oklahoma.
9- The design solution shall be a PV-ready. Because PV systems are currently not cost-effective, it is unlikely that the manufactured home may incorporate one. However, these circumstances may change in the foreseen future.
   [Note] According to the U.S. Census Bureau, median household income of all occupied manufactured homes is $27,885 as opposed to $41,775 for all occupied housing units in the country. That is 33% below the national median[5].
   [Note] FYI: Prices of OCI-built manufactured homes, as delivered and completed on site, range from $55 to $60 per square foot[6]. OCI-built units are considered to be the baseline for this design project (OCI is the state-owned Oklahoma Correctional Industries).

Aesthetics:

10- The design solution shall enhance the public's awareness of sustainability and generate a model for visually-pleasing manufactured homes. Although sustainable buildings may not look any different than normal buildings, appropriate expression of sustainable features may make a difference.

4.2 Students' Work Expectations

While solving this design problem as described above, students were expected to implement the integrated design method, in which quantitative evaluation of initial solutions should inform and direct subsequent design development(s). Quantitative evaluation of the environmental performance of the design schemes was based on the results of rigorous (and simplified) engineering methods. Calculations of both the passive heating and passive cooling systems were required. Figure 2 shows the calculation procedure to design the passive solar heating systems. Figure 3 shows the calculation procedure to design the natural ventilation systems.

4.3 Design Development Loop

In this phase, each group developed its own conceptual design in the light of a simultaneous evaluation of its environmental performance. This happened through a series of tasks the students were required to do. These tasks are listed below:

1. Define a baseline design (chosen to be the typical Oklahoma Correctional Industries design for manufactured homes of the popular size). An example is shown in Figure 4.
2. Design the passive solar heating system. An example calculation worksheet is shown in Figure 2. Detailed explanation of the passive heating calculations is in section 4.4.
3. Design the passive cooling system (natural ventilation). An example calculation worksheet is shown in Figure 3. Detailed explanation of the passive heating calculations is in section 4.4.
4. Design the BIPV system, to produce the maximum possible amount of electricity. For sizing PV systems, students used the calculator available on the NREL website (National Renewable Energy Laboratory)[7].

4.4 Passive Heating and Cooling Calculations

In the passive solar design (example in Figure 2), students were able to eliminate the need for mechanical heating during the winter, a case that happens when heat gain in one day equates heat loss during the same day. To minimize heat loss, students added more insulation; and to increase heat gain, students increased the size of south-facing glass. In the end, the thermal balance between heat gain and heat loss determined the appropriate size of south-facing glass needed for the critical case scenario. The critical case scenario is typically assumed to happen either on December 21st (the weakest sun in the year) or January 21st (the coldest month in the year). The Excel spreadsheet, students were required to use, is user-friendly and instantaneously calculates UA (overall heat transfer coefficient) and the Balance Point temperature of the dwelling unit. The calculations were comprehensive and took into account all relevant design data, i.e., outdoor temperature, thermostat temperature, hourly SHGF, design parameters, occupancy data, and the performance data of insulation, glass type, and the heat recovery unit.

For the passive cooling (example in Figure 3), students sized the windows for effective natural ventilation that is able to flush the heat built up inside the dwelling unit to the outside. This system is only effective when outside temperature is 80° F or lower. Calculations were comprehensive and took into account all relevant design data, i.e., intensity of heat gain due to solar and internal heat gain, wind speed and direction, and window type.

Passive Heating Calculations, Whole Building

Short Side - Wichita, KS - allen/stewart

Based on Balance Point Temperature Method. [Simplified]

Assumptions: (1) Shadow patterns per test models. (2) Enough thermal mass to evenly re-distribute heat over 24 hours. (3) Weekday. (4) Night insulation is used from sunset to sunrise. (5) R value of wall layers except insulation = 2 & R value of roof layers except insulation = 1

Location:

	Wichita, KS	37.65 ° NL
Average outdoor temperature °F:	33	Feburary 21
Thermostat temperature °F:	75.0	
Orientation:	South	
Actual solar heat gain factor (Btu/sq.ft):	1662.6	All day (south)
Sunshine hours:	10.7	Hours
Building's Balance Point:	27.5	°F

Design:

Total interior area (sq.ft):	943.0	
Area of roof (sq ft):	1716.0	Insulated
Area of exterior wall (sq ft):	110.0	South, including windows
Area of exterior walls (sq ft):	1160.0	All other, including windows
Area of windows (sq.ft):	110.0	South
Area of windows (sq.ft):	100.0	All other directions
Exposed perimeter (ft'):	0.0	
Net area of south wall (sq.ft):	0.0	Positive value!!!
Total area of exterior walls (sq ft):	1270.0	Including windows
Total area of windows (sq ft):	210.0	All directions
Net area of solid walls (sq ft):	1060.0	Excluding windows
exterior surface-to-area Ratio:	1.46	(roof + exterior walls) / interior area

Occupancy:

Number of people:	4.00	
Hours of occupancy/day:	14.00	night
People (Btuh/person):	270.00	
Light load (Watt/sq ft):	0.30	
Equip. load (Watt/sq ft):	0.03	
	Vital Signs	

Materials:

U roof:	0.023	
U wall:	0.036	
U glass:	0.310	day
U glass:	0.098	night
SC of glass:	0.620	
Heat recovery:	80.0%	
R roof insulation:	43.00	
R wall insulation:	26.00	
R added night insulation:	7.00	

1. Building Overall Heat Transfer Coefficient

UA-Building (day)	during day hours				Btuh/ °F	Formula:	
UA-Roof	1716.0 sq.ft	0.023 Btuh/sq.ft °F			39	UA = Area x U	Roof
UA-Net Solid Walls	1060.0 sq.ft	0.036 Btuh/sq.ft °F			37.857	UA = Area x U	Walls
UA-Glazed Windows	210.0 sq.ft	0.310 Btuh/sq.ft °F			65.100	UA = Area x U	Glass
UA-Exposed Perimeter	0.0 sq.ft	0.810 Btuh/ft °F			0.000	UA = length x U	Exposed Perimeter
UA-Ventilation	943.0 sq.ft	0.080 Btuh/sq.ft °F		0.2	15.088	Area x U x (1-Heat recovery %)	Ventilation
					157.045		

UA-Building (night)	during night hours (with night insulation)				Btuh/ °F		
UA-Roof	1716.0 sq.ft	0.023 Btuh/sq.ft °F			39	UA = Area x U	Roof
UA-Solid Walls	1270.0 sq.ft	0.036 Btuh/sq.ft °F			45.357	UA = Area x U	Walls
UA-Glazed Windows	210.0 sq.ft	0.098 Btuh/sq.ft °F			20.536	UA = Area x U	Glass
UA-Exposed Perimeter	0.0 sq.ft	0.810 Btuh/ft °F			0.000	UA = length x U	Exposed Perimeter
UA-Ventilation	943.0 sq.ft	0.080 Btuh/sq.ft °F		0.2	15.088	Area x U x (1-Heat recovery %)	Ventilation
					119.981		
			Hourly Average =		136.506 Btuh/ °F	UA = (UA day x day hours) + (UA night x night hours)/24	Space design

2. Average Hourly Internal Heat Gain

Heat gain (unoccupied)	during day hours			Btuh	Formula:	
Equipment	0.03 Watt/sq.ft	943.0 sq.ft	3.41	96.469	q = Power load x area of space x 3.41	Equipment
				96.469		

Heat gain (occupied)	during night hours			Btuh	Formula:	
People	4.00 persons	270.0 Btuh		1080.000	q = Number of people x Heat gain from one person per hour	People
Light	0.30 Watt/sq.ft	943.0 sq.ft	3.41	964.689	q = Light load x area of space x 3.41	Light
Equipment	0.03 Watt/sq.ft	943.0 sq.ft	3.41	96.469	q = Power load x area of space x 3.41	Equipment
				2141.158		
			Hourly Average =	1289.204 Btuh	Q = [(q x number of hours) + (q x number of hours)]/24	Occupancy

3. Average Hourly Solar Heat Gain:

Solar heat gain	during day hours			Btuh	Formula:	
Direct solar (South)	1662.6 Btu/sq.ft	110.0 sq.ft	0.62	4724.676	Solar Heat Gain = [(all day solar gain) x glass area x SC] /24	Direct
Direct solar (North)	184.3 Btu/sq.ft	100.0 sq.ft	0.62	476.058	Solar Heat Gain = [(all day solar gain) x glass area x SC] /24	Diffused
			Hourly Average =	5200.734 Btuh	Solar Heat Gain = direct + diffused	

4. Balance Point Temperature

At Balance Point Temperature, Net Thermal Exchange=zero — *Balance Point (T_b) = Thermostat Temperature - (Qi / UA total)*

ΔT = (Q_i / UA total)	47.5	°F
Thermostat Temperature	75.0	°F
Balance Point (T_b)	27.5	°F

COMPARE BALANCE POINT AGAINST THE AVERAGE OUTDOOR TEMPERATURE. 33.0 °F Feburary 21

Solar Harvesting

Calculate the Solar Heat Gain Factor (All Day), according to the testing of physical models.

		From Table		Corrections		Actual	
Feburary 21	% exposed	Direct	Diffuse	Elevation	Clearness number	South	North
7 AM	100.00%	17	3	1.030	1.000	17.5	3.1
8 AM	100.00%	94	11	1.030	1.000	96.8	11.3
9 AM	100.00%	155	17	1.030	1.000	159.6	17.5
10 AM	100.00%	199	22	1.030	1.000	204.9	22.6
11 AM	100.00%	225	24	1.030	1.000	231.6	24.7
12 NOON	100.00%	235	25	1.030	1.000	241.9	25.7
1 PM	100.00%	225	24	1.030	1.000	231.6	24.7
2 PM	100.00%	199	22	1.030	1.000	204.9	22.6
3 PM	100.00%	155	17	1.030	1.000	159.6	17.5
4 PM	100.00%	94	11	1.030	1.000	96.8	11.3
5 PM	100.00%	17	3	1.030	1.000	17.5	3.1
	SOUTH facing GLASS	SOUTH Btuh/sq.ft	NORTH Btuh/sq.ft		Urban Area	1662.6 Btu/sq.ft (All Day)	184.3 Btu/sq.ft (All Day)

Figure 2: Passive Heating Calculations Worksheet

Passive Cooling - Comfort Ventilation

Whicita Falls, TX - Allen/Stewart

Type of space: Residential

All exterior walls, roofs and windows are shaded
No impact of sol-air temperature
Solar heat gain is due to diffused component only
Design Condition is 15 ACH

STEP 1: Input Data

Location:			Design:			Occupancy:		
Solar Heat Gain Factor (diffuse)	40.0	Btuh/sq.ft	Area of space (to be ventilated)	943.00	sq.ft.	Number of people	4	person(s)
Wind Speed (airport)	11.0	mph (from NOAA maps)	Area of all glazed windows	200.00	sq.ft.	Metabolism	270	Btuh
Wind effectiveness factor (setting and height)	0.4	(from Figure 3)	Shading Coefficient of glass (SC)	0.62		Equipment load	0.3	W/sq.ft
Wind effectiveness factor (azimuth)	1.0	Wind is perpendicular	Area of the wind-facing exterior wall	528.00	sq.ft.	Light load	0.0	W/sq.ft
Effective wind speed	4.4	mph	Stack height (if any)	7.00	ft			

STEP 2: Calculation of Peak Heat Gain (during the cooling season) (assumed on July 21st)

							Formula:
Windows	40.00 Btuh/sq.ft	200.00 sq.ft.		0.62	4960	Btuh	= SHGF x Glass x SC
Solid Walls & Roof	NA	NA			NA	Btuh	ignored if all walls and roof are shaded
People	4.00 person(s)	270.00 Btuh			1080.00	Btuh	= number x metabolism of each
Equipment	943.00 sq.ft.	0.30 Watt/sq.ft	3.41		964.69	Btuh	= area x equipment load x 3.41
Lights	943.00 sq.ft.	0.03 Watt/sq.ft	3.41		96.47	Btuh	= area x light load x 3.41
Total Peak Heat Gain					7101.16	Btuh	= SUM of the above
				Intensity of Peak Heat Gain	7.53	Btuh/sq.ft	= total peak heat gain / area of space

STEP 3: Calculation of Size of Openable Windows - CROSS VENTILATION

Intensity of Peak Heat Gain	7.53		
Effective wind speed	4.4		
Required free inlet area	2.5	%	
Effective open area of operable windows	0.45	(from Figure 4)	
Gross area of operable windows	52.39	sq.ft.	without insect screen
	174.63	sq.ft.	with insect screen (30% net free area)

STEP 4: Calculation of Size of Openable Windows - STACK EFFECT VENTILATION

Intensity of Peak Heat Gain	7.53		
Effective wind speed	4.4		
Required free inlet area	30	%	
Effective open area of operable windows	0.45	(from Figure 4)	
Gross area of operable windows	628.67	sq.ft.	without insect screen
	2095.56	sq.ft.	with insect screen (30% net free area)
Effective open area in stack	0.75	(from Figure 4)	
Gross area of opening in stack	377.20	sq.ft.	without insect screen
	1257.33	sq.ft.	with insect screen (30% net free area)

NOTE: Gross area of operable windows cannot exceed total area of the exterior wall.

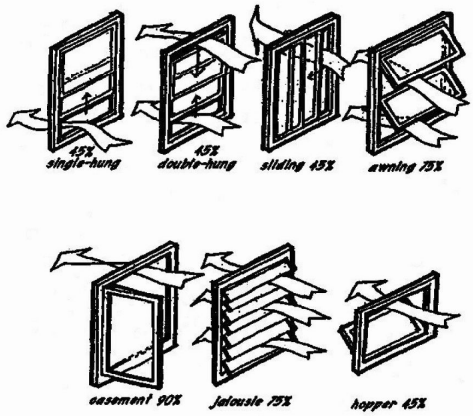

Figure 4: Effective open area of various window types. *(Redrawn from Vieira and Sheinkopf, 1988, by permission.)*

Source of figures 1,2 & 4: EC Systems, by F. Moore, 1993, p. 191 & 193.
Source of figure 3: MEEB, 10 Edition, by Stein et al, 2006, page 290 .

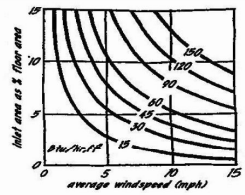

Figure 1: Cross-ventilation rule of thumb, for heat removed per unit of floor area, and the relationship of inlet opening area and wind speed. Total inlet opening area is expressed as a percent of total floor area. Note that the method assumes the outlet areas at least equal to inlet area and internal air temperatures are at least 3°F higher than the exterior. *(Redrawn from Reynolds, 1984, by permission.)*

[FIGURE 1] Use this figure to determine % area of window to floor area Cross Ventilation

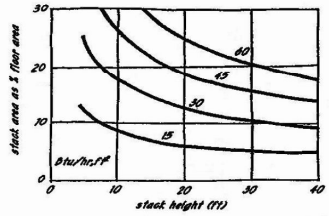

Figure 2: Stack-effect ventilation rule of thumb, for heat removed per unit floor area. The total stack area is the minimum of: inlet free area, cross section through the vertical stack, and outlet free area. Internal air temperatures are assumed to be at least 3°F higher than the exterior. *(Redrawn from Reynolds, 1984, by permission.)*

[FIGURE 2] Use this figure to determine % area of window to floor area Stack Effect Ventilation

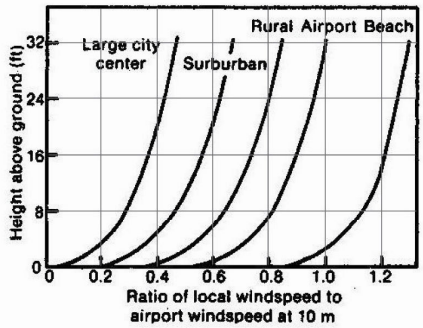

Figure 3: *Wind speed variation with height for various terrains. (From* Cooling with Natural Ventilation, *Florida Solar Energy Center, published by the Solar Energy Research Institute.)*

[FIGURE 3] Use this figure to determine the effective wind speed.

Figure 3: Passive Cooling Calculations Worksheet

4.5 Final Evaluation

Evaluation of the final submission was according to the following criteria:

- Pleasant architectural design of the manufactured home.
- Low-energy performance of the home, i.e., minimum use of purchased energy.
- Adaptability of the design for different climates and site placements.

Figure 4: OCI-manufactured home, as currently designed.

5. Students' Work

Students were enthusiastic, positive, and eager to learn. They met (and some exceeded) the expectations and followed the process detailed above. They produced impressive results. This section of the paper presents the results of students' work and their learning experience during the pre-design analysis phase.

5.1 Pre-Design Climatic Analysis

As a result of students' investigation prior to the actual design started, they were able to accurately frame the problem and define a set of specific performance-based targets for the design process. Students got familiar with a user-friendly bioclimatic design-assisting tool, which is the Climate Consultant computer program. Students used the program to generate initial bioclimatic recommendations for the design of the Chameleon House. Figure 5 shows the recommendations for Wichita, Kansas (the northern edge of the targeted region), and Figure 6 shows the same for Wichita Falls, Texas (the southern edge of the targeted region). The climate of Oklahoma calls for both heating and cooling with temperatures as low as 7° F in winter (Wichita, KS), and as high as 101° F in summer (Wichita Falls, TX). Students also generated the solar data necessary to design the passive heating system for the Chameleon House (Wichita, KS data) and generated the wind speed and direction data necessary to design the passive cooling system (Wichita Falls, TX data).

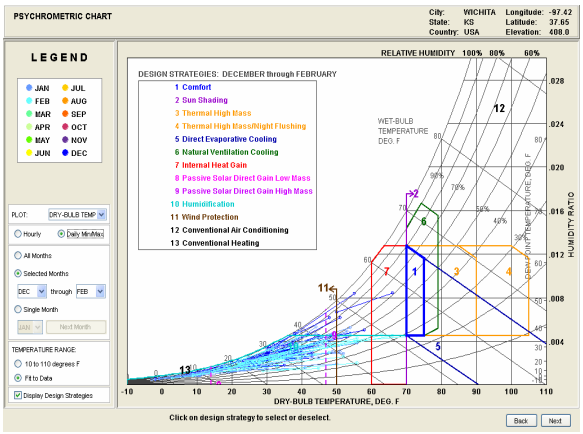

Figure 5: Winter conditions in Wichita, KS.

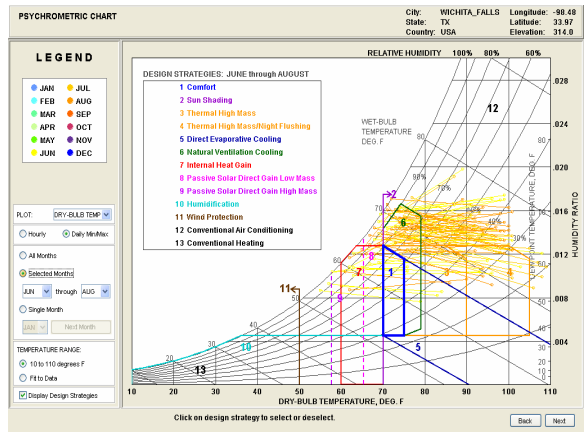

Figure 6: Summer conditions in Wichita Falls, TX.

Investigation of local examples of energy-efficient single family homes lead students to the Millennium House in Tulsa, OK. The two successful sustainable measures utilized in the Millennium House were: building the walls using the insulated concrete forms (heavy mass + super insulation), and the use of the ground source heat pump.

Data gathering of energy efficiency-oriented design recommendations (for single family homes) produced a long list of design recommendations that is applicable to the Chameleon House. Students searched recommendations published by the Department of Energy, Energy Star program (EPA), US Green Building Council (LEED-H), NAHB (builder's guide for mixed climate), and the International Energy Conservation Code (IECC-2006).

5.2 Pre-Design Research

Besides the pre-design climatic analysis, students also searched for similar type of green projects. The focus of this study was the houses built to meet the requirements for the Energy Star program, which is administered by the EPA (U.S. Environmental Protection Agency).

Students looked at a number of case study buildings, including local and national projects. However because of the nature of this project, students focused on local projects. Students were encouraged to study the site-built Energy-Star homes built by Ideal Homes, which is the largest homebuilder in the State of Oklahoma that was also named as America's Best Builder in 2007. The result of this study was to recognize a list of energy-saving measures that are achievable and worked locally, which included: blown-in insulation for walls and ceiling; perimeter insulation in foundation; radiant heat barrier roof sheathing; air seal polycel caulking around windows, doors, joints and sill plates; insulated and mastic sealed ducts; technologically advanced fresh indoor air ventilation system with motorized damper and fan recycler; passive attic vent with soffit chutes; high performance Low-E windows; tank-less water heaters; and Energy-Star appliances[8].

Students also visited a local off-grid residence near Oklahoma City. This house relies on a hybrid wind-PV system to generate its own electricity, and implements passive solar heating to meet the heating demand during winter.

5.3 Students' Projects

By the end of the project and based on students' designs, it can be stated that: a manufactured house can be ultra energy-efficient using over-the-shelf technology and common construction materials. "Good Design Matters!" The benefits of the inter-disciplinary/integrated design method were highlighted to the students, who experienced its vital role to guide the design process towards energy efficiency. With the use of user-friendly simplified engineering tools, students were able to evaluate the performance of their designs and were able to produce a variety of design solutions that met the success criteria for the Chameleon House. Students were innovative and produced non-traditional schemes that are both aesthetically pleasing and highly energy efficient. Four design schemes are presented below.

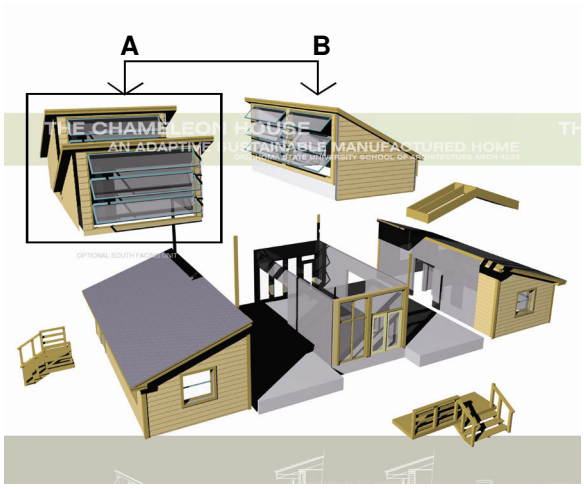

Figure 7: The Rotating Solar Cap

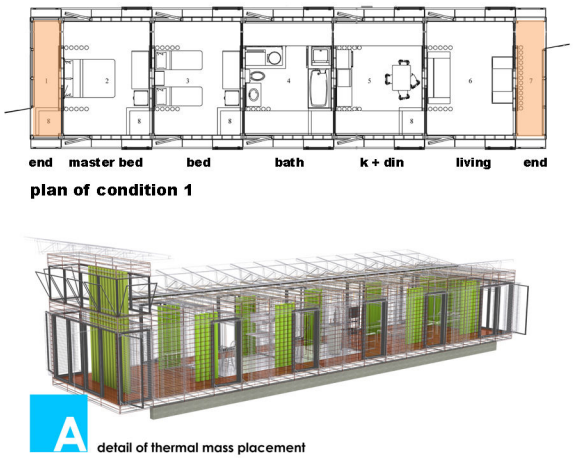

Figure 8: A Room-by-Room Assembly

Scheme 1: The Rotating Solar Cap [Fig. 7]

This concept design is simple and versatile at the same time. For any site placement of the house itself, a rotating solar cap can be installed to face due south. The house itself comes in three pieces; the living room and two flanking wings. The solar cap is placed on the top of the living room. The solar cap is shipped separately and comes in two designs (A or B in Figure 7) depending on the south direction.
Total area of the house is 1,200 sq.ft. Excluding the electricity that is generated by a BIPV system, the house saves up to **44.21%** of the annual energy consumption compared to an all-electric similar-size super-insulated house in Oklahoma.

Scheme 2: A Room-by-Room Assembly [Fig. 8]

This concept design is expandable over time. Each room in the house can be manufactured and ordered separately, then (on site) all pieces are assembled together in a linear manner. This 1,100 sq.ft. house is two-bedroom (as shown in Figure 8), and can expand to 1,320 sq.ft. with the purchase of one more room-module. Passive heating is provided by the glazed French windows along the two long sides. However, in case the short side of the house is facing south, an

additional end-piece (shaded areas on the plan in Figure 8) that includes an indirect passive heating system can be attached onto that short side. Low-cost cooling is possible with the operation of a whole house fan that is integrated into the tall end piece. Excluding PV electricity, this house saves up to **40.63%** of the annual energy consumption.

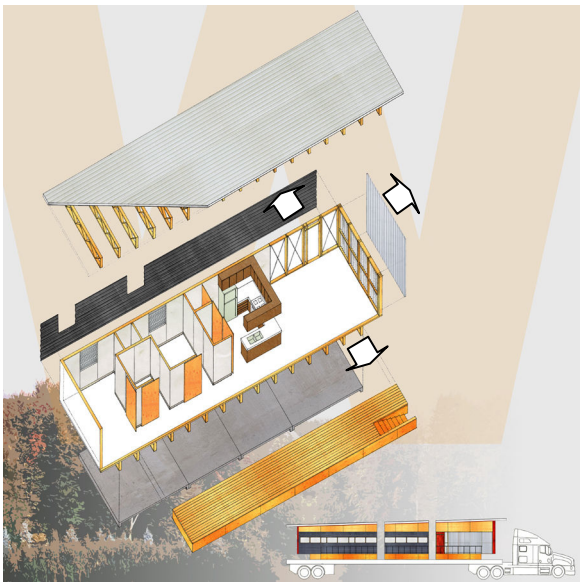

Figure 9: Anchored to the Sun

Figure 10: The Footless Print

Scheme 3: Anchored to the Sun [Fig. 9]

In this concept design, the house is anchored to the sun (south direction) by its living room. The living room enjoys three different exterior exposures (the arrows in Figure 9), which allows it to face the sun regardless of the site placement. An adequately-sized indirect passive heating system is attached to the living room on its south-facing wall. Only if south is on the master bedroom side, the indirect passive heating system can be attached to the master bedroom's solid wall. This 1,024 sq.ft. house can be shipped in three pieces on one semi-truck as shown in Figure 9. Excluding PV electricity, this house saves up to **38.44%** of the annual energy consumption.

Scheme 4: The Footless Print [Fig. 10]

This concept design does not only conserve energy but also the land. To minimize its impact on the planet, this Chameleon House is elevated on expandable pedestals. This 943 sq.ft. house is narrow and long, so it can be shipped on a single semi-truck. To provide passive heating, multiple windows face the four directions. Adjustable external shading devices protect windows in summer and allow the sun into the inside in winter. PV panels, mounted on the adjustable shading devices, produce electricity year round. The space underneath the house can be used as a carport or a shaded outdoor living area. The roof is accessible and can be used during temperate climatic conditions. Including the electricity generated by the PV, this house can save up to **48.7%** of the annual energy consumption.

5.4 Summary of Findings

These concept designs were successful. They also proved the following:

- The interdisciplinary approach applied through the integrated design process contributed the most to the success of this student design project. Feedback from the thermal load calculations helped the students to make the right decisions in the right time (early enough during the design process).
- Using over-the-shelf technology can result in significant energy savings. In this project, students used commercially available glass and insulation, and other common construction materials.
- In Oklahoma (with the help of night insulation) **100%** passive heating is possible even during extremely cold and long winter nights.
- The design of an add-on indirect (or isolated) heat gain system may have a potential demand in the market. This add-on system, if designed to be independent from site placement, can be used in a wide-variety of single-family homes. The Rotating Solar Cap scheme is an evidence of that.
- In Oklahoma, natural ventilation cannot provide cooling during all summer months. However, the whole house fan can provide an effective low-cost cooling that can save up to **45%** of cooling energy.
- Super insulation, coupled with thermal mass, can enhance the performance of manufactured homes in summer and winter, and are essential to making 100% passive solar heating possible.

6. Faculty Observations

The use of the P3 student sustainable design competition was a successful tool to introduce multi-disciplinary (or inter-disciplinary) design processes to students. Our observation was that the students although challenged with the complexity of the task, were also very enthusiastic and eager to solve the problem and reach a successful solution. Our understanding is that: because the objective of the design problem was quantifiable students were able to prove and verify that their designs achieved the predetermined goals of the design process.

Along the process, students also got familiar with the engineering principles of thermal load calculations, and the design of passive environmental building systems. In this course, students learned about the following:

- The nature and definition of sustainable architecture, as a new generation of buildings that perform efficiently and are environment-friendly.
- Principles of bioclimatic design as they apply to the design of buildings and building systems.
- Design of passive solar heating systems.
- Design of passive cooling systems (natural ventilation).
- Internal heat gain in buildings and its impact on the performance of buildings.
- Properties of common construction materials and the impact of these materials on human comfort and the environmental performance of buildings.
- Design of the building envelope.
- Optimum design and sizing of PV systems.

7. Conclusions

This experimental educational experience supports the following conception:

- The use of sustainable design problems is a successful vehicle to introduce the principles of interdisciplinary/multidisciplinary design to students.
- Implementation of the integrated design method is crucial to explain the relationships between the different disciplines involved.
- Students understand the direct and indirect relationships between different disciplines much more effectively (and painlessly) when they are asked to work on a long-enough design problem/project. Simple homework assignments that do not provide the opportunity for discussion or re-design cannot provide the same experience.
- It is of a paramount importance to establish a clear quantifiable goal for an interdisciplinary design process. If the design challenge has to satisfy multiple goals, one or few of these goals should be highlighted as the basis for evaluation.
- In the field of green design, although LCA (Life Cycle Analysis) is the best tool to evaluate design decisions, it is still inconvenient to implement the LCA in the classroom. This is mainly because the currently available LCA tools are either inaccurate or not user-friendly.

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